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# **LTO-9: RAISING THE BAR AGAIN FOR PERFORMANCE, CAPACITY, AND DATA RELIABILITY**

A TECHNICAL BRIEF

An abstract graphic at the bottom of the page consists of several overlapping triangles. The top triangle is a bright blue. Below it is a darker blue triangle. The bottom-most triangle is a deep red. The triangles overlap in a way that creates a sense of depth and movement, with the red triangle appearing to be in the foreground.

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## Introduction

Since its introduction at the turn of the 21st century, the Linear Tape Open (LTO) tape format has become the market-dominating standard for digital magnetic tape drives and media. Originally released with a 100GB cartridge and a 4-generation roadmap, LTO has delivered on its promise of continuous improvement, with a new generation of technology released every few years. Thanks to advancements in materials and methods, today there is clear visibility to a 14th generation and beyond.

With the modern data explosion, magnetic tape as a storage medium has not just remained relevant, its relevance has increased. More than ever, tape is the archive medium of choice due to its reliability, long-term data durability, density, performance, and low cost. The largest use of tape today is as a cold storage tier in hyperscale public clouds, and nearly all is LTO tape.

The LTO Consortium ([www.lto.org](http://www.lto.org)) is the organization founded to develop and promote LTO Technology. The consortium has three main members, Hewlett-Packard Enterprise, IBM, and Quantum, known as the technology provider companies, or TPCs. The TPCs jointly develop and contribute the hardware and software technology that drives the evolution of LTO. In addition to the TPCs, the consortium has many other members who participate in a variety of ways. Quantum has contributed technology and expertise in many areas, including servo format, information encoding, decoding, and error recovery, capacity-efficient partitioning, and data reliability/durability analysis and modeling.

This technology brief provides a detailed description of technology improvements in LTO-9 tape drives and media which have increased capacity, performance, and reliability. As with previous generations, the LTO-9 drive is available in two form factors: full-height (FH) and half-height (HH). It's important to know that these drives differ in more than physical size. A later section of this document compares the two form factors to help customers understand which is best for their environment and use case.

## Comparing LTO-8 and LTO-9 Specifications

Highlights:

- Capacity: 50% increase
- Performance (transfer rate): 11.1% increase
- Data Durability: 10x improvement

Feature	LTO-7 (All)	LTO-8 Half Height	LTO-8M Full Height	LTO-8 Full Height	LTO-9 Half Height	LTO-9 Full Height
Native capacity	6 TB	12 TB	9 TB	12 TB	18 TB	18 TB
Compressed capacity	15 TB	30 TB	22.5 TB	30 TB	45 TB	45 TB
Native performance	300MB/s 1.08 TB/hr	300MB/s 1.08 TB/hr	300MB/s 1.08 TB/hr	360MB/s 1.3 TB/hr	300MB/s 1.08 TB/hr	400MB/s 1.44 TB/hr
Compressed performance	750 MB/s 2.7 TB/hr	750 MB/s 2.7 TB/hr	750 MB/s 2.7 TB/hr	900 MB/s 3.24 TB/hr	750 MB/s 2.7 TB/hr	1,000 MB/s 3.6 TB/hr
UBER	1 in 10 <sup>19</sup>	1 in 10 <sup>19</sup>	1 in 10 <sup>19</sup>	1 in 10 <sup>19</sup>	1 in 10 <sup>20</sup>	1 in 10 <sup>20</sup>
Read back to	LTO-5	LTO-7	LTO-7	LTO-7	LTO-8	LTO-8
Write back to	LTO-6	LTO-7 M8	LTO-7 M8	LTO-7 M8	LTO-8	LTO-8

Table 1 - LTO-7 Through LTO-9 Basic Specifications

## Technology Improvements, Changes, and New Features

Technical Feature	Units	LTO-8	LTO-9	Change
Nominal Capacity	TB	12	18	+50%
Transfer Rate	MB/s	300	400	+33%
Areal Density	Gb/in <sup>2</sup>	8.5	11.9	+40%
Tape Length	m	960	1,035	+8%
Tape Thickness	µm	5.6	5.2	-7%
Number of Wraps	#	208	280	+35%
Track Density	TPI	16,282	21,897	+35%
Number of Tracks	#	6,656	8,960	+35%
Size of Data Set	MB	5.031	9.805	+95%
UBER	User Bits	10 <sup>19</sup>	10 <sup>20</sup>	+10%
Data Durability	# of Nines	11	12	+5%
Cartridges per UBER Event	#	104,167	694,444	+6.7x

Table 2 – Technology Changes &amp; Improvements Summary, LTO-8 to LTO-9

### Capacity

LTO-9 relies on several technological advancements to achieve a 50% increase in capacity. Overall areal density was increased by 42%, from 8.5Gbp<sup>2</sup> to 12Gbp<sup>2</sup>. This increase was mainly achieved by increasing track density, with the number of tracks per inch increasing 35% from 16,282 to 21,897, and a corresponding 35% increase in the number of total tracks from 6,656 to 8,960 and total wraps from 208 to 280. Linear density was also increased by 3.8%.

The new, narrower track width was achieved through a combination of improvements in tracking performance, new, narrower tunneling magnetoresistive (TMR) readers within the head assembly (now <1000nm in width) and optimized writers. The narrower tracks also necessitated improvements to the media magnetic layer. Magnetic particles are Barium Ferrite (BaFe) as in LTO-8, but with improved characteristics to support the higher linear densities.

Changes were also made to the tape substrate, with the thickness reduced by 7% from 5.6µm to 5.2 µm. This in turn enables more tape to fit on the reel – tape length per cartridge has increased from 960m to 1035m. The new substrate also features optimized stability characteristics to mitigate tape dimensional variations that occur due to fluctuations in environmental conditions.

## Performance

Several techniques may be used to increase the transfer rate of a tape drive. Increasing linear density delivers more bits per mm along the tape. Increasing track density and number of tracks delivers more bits per mm across the tape. Higher tape speed puts more bits past the head per unit time. All three of these techniques have been used in various LTO generations. For LTO-9, the linear density was increased by 3.8%, to 21,459 bits/mm from 20,668 bits/mm in LTO-8. The max tape speed was also increased by 7.3%, to 6.059m/s from 5.645m/s in LTO-8. These increases were made possible by a new optimized tape path, new tracking servo, and new ASICs, and combined produce the 11.1% increase in native throughput.

## Data Integrity

The LTO ECC format has always been based on a two-dimensional interleaved dual error-correction code, where the inner code (C1) is operated in error detection and correction mode, and the outer code (C2) is in erasure mode. LTO's unique two-dimensional interleaving algorithm spreads data physically around the tape to randomize the effects of media defects and burst errors. This randomization enables ECC to work efficiently, resulting in extremely low uncorrectable bit error rate (UBER) numbers. LTO-9 has a new C2 format of (192,168,25) compared to the LTO-8 C2 format of (96,84,13). The LTO-9 code word is doubled in length, with more parity. This new C2 ECC is the key to achieving even lower UBER numbers compared to LTO-8 while also achieving greater areal density. It is this change that made it possible for the UBER detection specification for LTO-9 to be increased to no more than a single bit error for every  $1 \times 10^{20}$  of user bits transferred, a 10x improvement over LTO-8.

The LTO UBER specification is based on a calculation of uncorrectable C2 ECC events, assuming all errors are random and uncorrelated, an assumption which has been experimentally verified as being realistic. This is necessarily a theoretical, not experimental analysis. To verify a UBER of  $1 \times 10^{20}$  in a statistically significant way would require running a year-long experiment using tens of thousands of tape drives and tens of millions of pre-written cartridges, which is economically infeasible. These theoretical calculations are based on LTO-9 with a 32-channel, multi-dimensional, deep-interleaving format architecture, and the new ECC format with advanced BaFe media. More complex reliability models, which are based on the theory of renewal processes, can account for correlated errors and defective header and synchronization fields [1].

UBER calculations are based on single-pass decoding, which is the technique used in LTO-8 and prior generations. LTO-9 can perform iterative decoding, wherein multiple rounds of C1/C2 decoding are used to improve error correction performance.

In addition to providing higher reliability in the face of uncorrelated errors, LTO-9 is also more resistant to certain types of correlated errors, such as the temporary loss of read channels that can occur due to debris clogging the head. With one failed read channel and an input error rate of  $10^3$ , LTO-8 UBER falls from  $10^{19}$  to  $10^{16}$ . LTO-9 maintains a UBER of  $10^{20}$  with 4x the input error rate,  $4 \times 10^3$ . LTO-9's performance with two failed read channels is even more impressive, providing UBER of  $10^{19}$  at an input error rate of  $10^3$ , while the UBER of LTO-8 under the same conditions falls to  $10^{10}$  [2].

Between the new iterative decoding logic and additional resistance to common correlated errors, it is likely that real-world LTO-9 UBER is significantly lower than the official specification.

For a more detailed discussion of LTO-9 drive encoding and UBER calculations, refer to the paper entitled "LTO-9 Technology and User Data Reliability Analysis" available at the LTO Consortium website here: <https://www.lto.org/wp-content/uploads/2022/08/LTO-UBER-Technical-Paper-August-2022.pdf>

## Tape Dimensional Stability (TDS) and the Calibration Process

Managing the dimensional characteristics of LTO tape as the media gets thinner and track densities increase is a critical technical challenge. When the increasingly common active archive use case is considered, where tapes are used as long latency random access devices, dimensional changes of media become a dominant variable to manage.

Magnetic tape media may appear to be a completely uniform, inert, unchanging strip of plastic, but unfortunately this is not the case. Tape media is a coated viscoelastic polymer with complex physical properties. Numerous, variable external factors alter its shape. Like other materials - paper, for example - the dimensions of a piece of tape media will change depending on temperature, humidity, and physical stresses that result from winding the media onto a reel. With LTO-9 having thousands of longitudinal data tracks sharing a strip of media approximately one-half inch wide, changes in media dimensions (primarily width) challenge the tape drive's ability to maintain tracking. Advanced techniques are required to measure, account for, and actively manage tape dimensions during both writing and reading to ensure data durability over time and at scale.

Temperature affects media width, but by a smaller percentage compared to humidity, which accounts for up to eight times as much dimensional change. Media width is also affected by tension, which is under the control of the drive firmware and algorithms over a limited range. Consider a common rubber band – as it stretches, the band's width is reduced, and as tension is released, width increases back to nominal. This same effect occurs with LTO tape media. As tape is wound on the cartridge reel, circumferential and radial stresses naturally occur, the dynamics of

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[1] S. S. Arslan, J. Lee, J. Hodges, J. Peng, H. Le, and T. Goker, "MDS Product Code Performance Estimations Under Header CRC Check Failures and Missing Syncs," IEEE Transactions on Device and Materials Reliability, vol. 14, no. 3, Sept. 2014.

[2] S.S. Arslan, M. Lantz, S. Furrer, G. Spratt, and T. Goker, "LTO-9 Technology and User Data Reliability Analysis," <https://www.lto.org>, August 2022

which are well understood. As a result, the shape of a strip of media wound in a cartridge is not a perfect rectangle, but a slight trapezoid whose dimensions are further affected by temperature and humidity, as shown in the figure below.

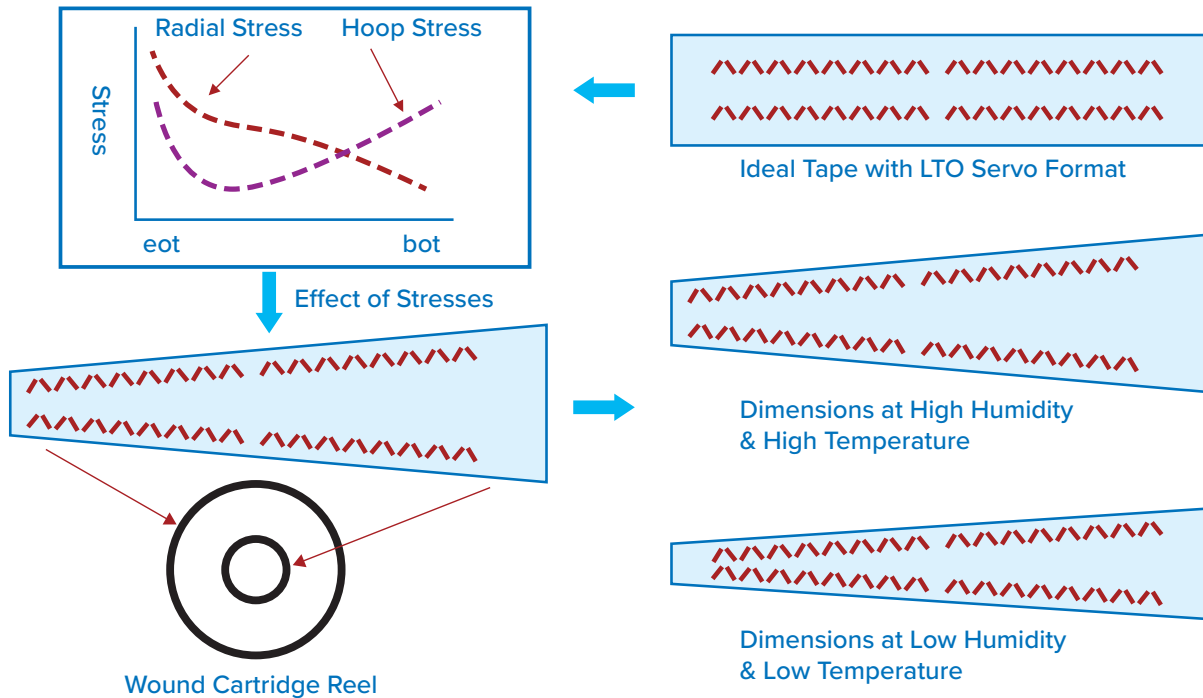


Figure 1 - Effects of Wound Stresses and Environment on Media Dimensions

To maximize the likelihood that any data written to a cartridge may be successfully read, even in different environmental conditions and decades later, LTO-9 introduces a new procedure known as cartridge calibration.

LTO drives are designed to manage and compensate for a range of tape dimensional conditions. Previous generations of LTO used tension control as a secondary means to control track position during reads. Like the rubber band example above, higher tension temporarily reduces media width and thus track spacing and position. LTO-9 uses tension control as a primary way to manage tape width, and therefore track position, during writes. For this method to be effective, the drive must know the actual dimensions of the media from beginning of tape (BOT) to end of tape (EOT). Calibration is the process used to take measurements of the media lateral dimensions, with the results stored in the cartridge memory chip. The goal of calibration is to allow data tracks to be placed on the media in the most optimal locations. This will provide the highest chance that the media can be successfully read in the future, even decades later and under different environmental conditions than the original write.

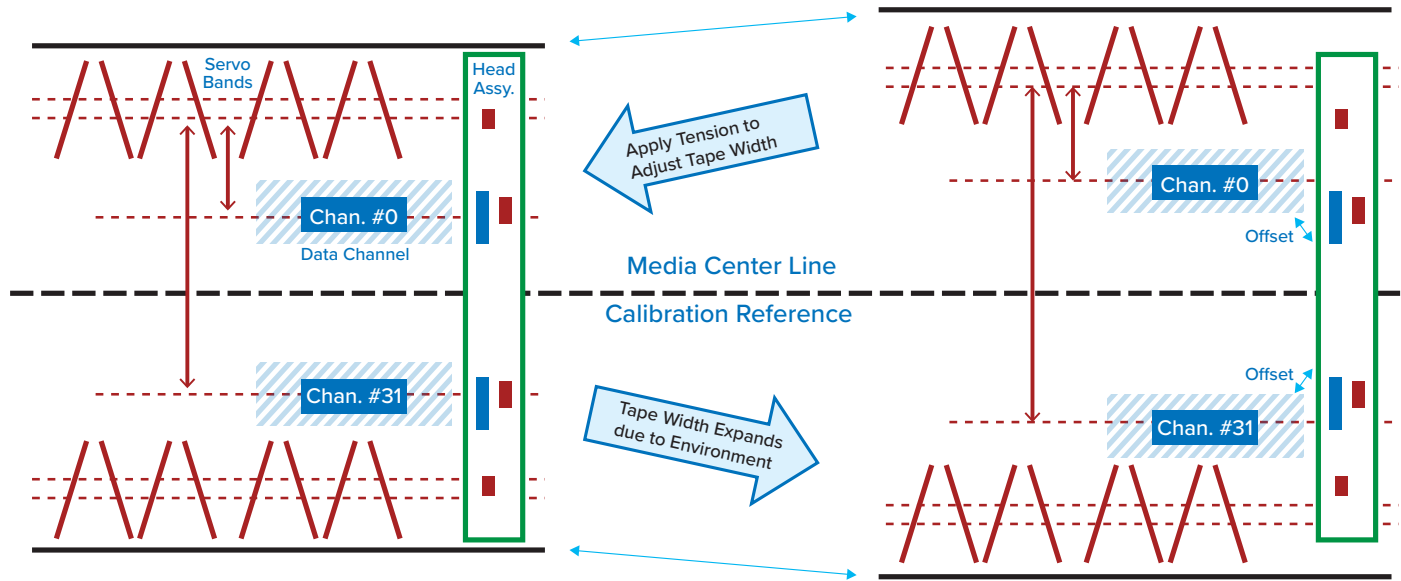


Figure 2 - Correction of Expanded Lateral Dimension of Media using Tension

Calibration establishes the dimensional signature of the media in a cartridge, optimized for the operating environment. When a new cartridge is loaded into a drive, calibration first ensures that the media is stabilized in equilibrium with environmental conditions within the drive, specifically temperature and humidity. LTO-9 drives contain sensitive temperature and humidity sensors directly in the tape path to assist with this process. The drive spools the media back and forth between the cartridge and the drive's take-up reel to expose it to the air, bringing it into equilibrium. Once the media is fully stabilized, the drive measures the tape width from BOT to EOT. Measured reference values are stored in the Cartridge Memory (CM) chip and are used to control tension during later operations, especially writing.

### Archive Mode Unthread

As mentioned above, tension affects the width of tape media, and tape is under tension when it is wound on the cartridge reel. Tension variations occur within the cartridge tape pack based on how the cartridge has been used – how much tape was spooled out of the cartridge into the drive, the number of passes made while writing or reading various regions of the media, etc. Tape width also changes due to tension over time, for example media wound within a cartridge sitting on a shelf for years, a factor known as ageing.

To maximize the ability to read data archived to LTO-9 media, even after many years or decades, LTO-9 drives use a cartridge unloading method known as Archive Mode Unthread. Archive Mode Unthread ensures the tape media is packed on the cartridge reel with even, optimal tension appropriate for archive storage.

When the drive receives a cartridge unload request, it first determines if the media has been moved from BOT. If not, the cartridge is simply unloaded. If the media has been moved from BOT,



the drive spools the media all the way to EOT, if it is not there already. Once at EOT, the drive will re-wind the media into the cartridge back to BOT using a pre-programmed tension profile that optimizes the media for archival storage.

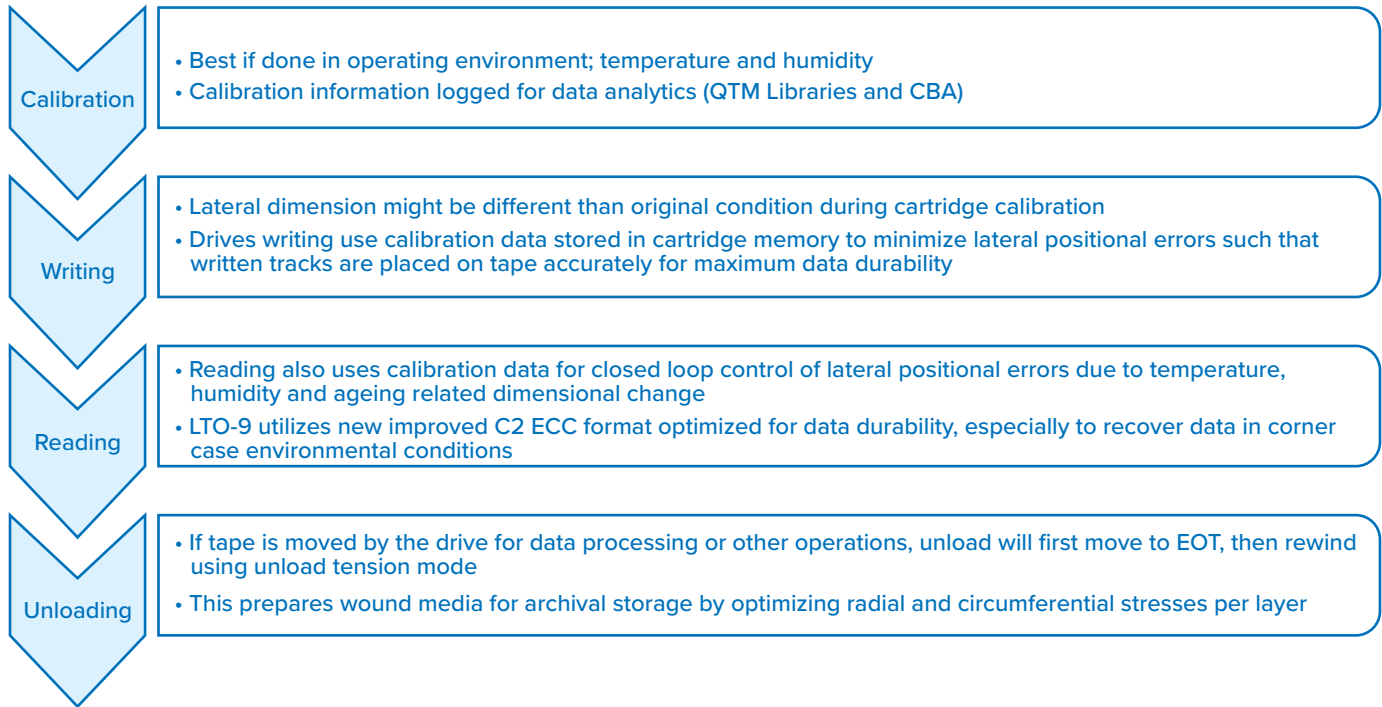


Figure 3 - Typical LTO-9 Calibration TDS Compensation Process

## Open Recommended Access Order (oRAO)

Due to the physical form factor of the media, tape is not well suited to random-access workloads. Traditionally hosts process tape read requests one at a time, in order. In busy environments with many reads occurring, this can result in large amounts of tape motion, as the drive spools the media back and forth to service reads in order, regardless of the relative position of the data on tape. This excess motion equals excess wear on drives, cartridges, and media, and it increases the “seek time” between reads.

oRAO, new to LTO with LTO-9, provides a method for applications to take advantage of the drive’s awareness of the physical location of records on tape. New SCSI commands have been added to enable this feature, which require application support. By eliminating wasted tape motion, oRAO can greatly improve retrieval times while reducing wear on drives and media.

When an application that supports oRAO has knowledge of multiple retrievals that need to be performed using the same LTO-9 cartridge, it first sends the list of needed user data segments to the drive with the new GRAO (Generate Recommended Access Order) command. Based on its knowledge of the physical position of the requested records on the media, the LTO-9 drive will sort

the submitted list into the most efficient retrieval order. When the application subsequently sends the RRAO command (Retrieve Recommended Access Order), the drive returns the sorted list of user data segments. Finally, the application uses standard read commands to access the user data segments in the recommended order.

The oRAO feature is not available in LTO-9 Half-Height drives.

## Comparing LTO-9 Full-Height (FH) vs. LTO-9 Half-Height (HH) Drive Form Factors

LTO-9 is available in both FH and HH drive form factors. It's important to understand the differences to select the appropriate drive for a given operating environment or application.

Most of the technology in LTO tape drives is shared between both FH and HH form factors. There are important differences, however, mostly due to the FH drive having more real estate for the circuitry and mechanical assemblies. The following table shows how the two drives differ, and the paragraphs below the table discuss the practical ramifications of these differences.

Technical Specification	LTO-9 FH	LTO-9 HH
MSBF: cartridge load/unload cycles	300,000	80,000
Encryption LED	No	Yes
Tape speed (maximum during locate/search)	10 m/sec	9 m/sec <sup>2</sup>
Tape speed (maximum during rewind)	10 m/sec	9 m/sec <sup>2</sup>
Acceleration	10 m/sec <sup>2</sup>	5 m/sec <sup>2</sup>
Reposition Duration (back hitch)	3.6 sec	5.2 sec
Average time to record from load point	45 sec	60 sec
Average rewind time	52 sec	62 sec
Cartridge insertion force (required)	1,530 gm	1,000 gm
Cartridge insertion force (maximum allowed)	3,060 gm	1,500 gm
Max shock during operation	30 G	10 G
Max vibration during operation	0.67 G	0.30 G

Table 3 - Full-Height vs. Half-Height Drive Specifications

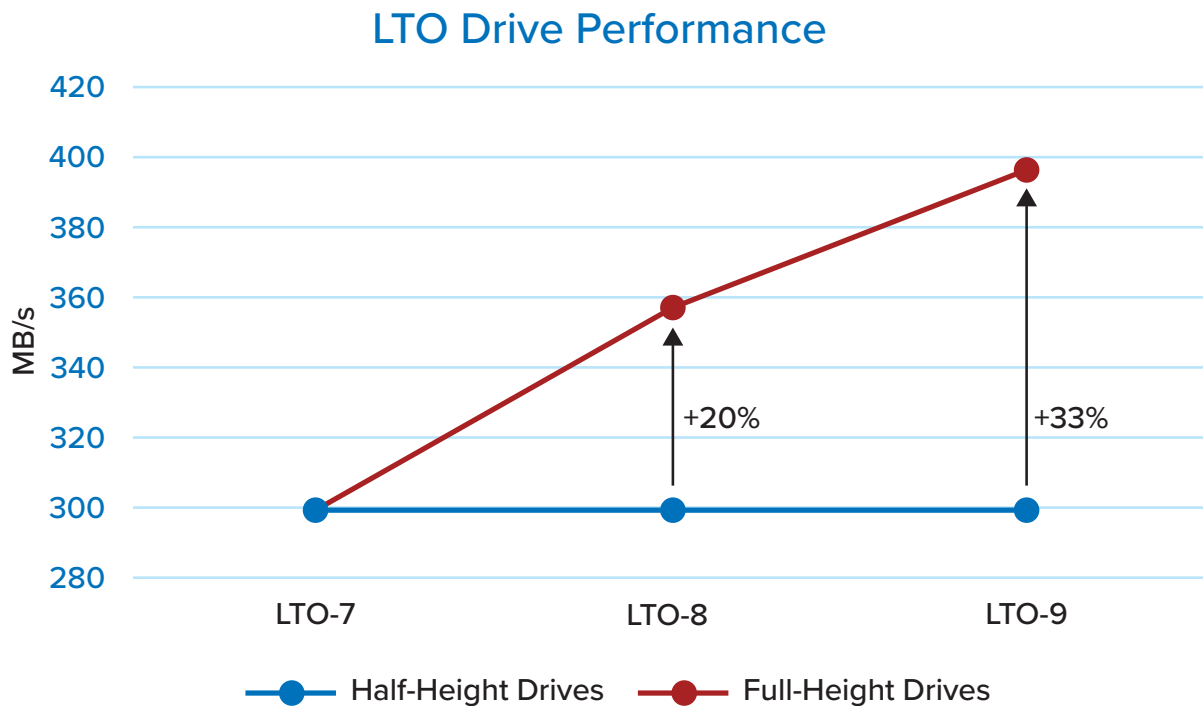
**Larger motors:** A simple place to start understanding these differences is size. The FH drive has significantly more space to allow for the use of larger and more robust mechanical assemblies, increased airflow for cooling electronics, as well as the use of larger motors that move the tape during writing, reading, and positioning.

The use of larger motors in the FH drive provides several advantages over the HH version of LTO-9:

- **Increased mechanical reliability:** The use of larger motors in this part of the LTO drive operation is relatively simple mechanics. Even though both the FH and HH drives have the same reliability ratings, by using larger motors to move the recording media, the larger motors are operating at a much lower percentage of the designed maximum load. Ultimately, this will increase the overall mechanical reliability of the tape drive.
- **Faster media movement:** The FH LTO-9 drive moves media faster than the HH drive; and in use cases where files are being accessed randomly from various locations on the cartridge, this can have a significant impact on the overall sustained data performance rates. For customers using the Linear Tape File System (LTFS) feature of LTO, this may be particularly true in that files are stored as they are written, and there is no way to predict which files are going to be accessed prior to the actual read request being received.
- **Faster media acceleration:** Another advantage of the larger motors in the FH drive is media acceleration. Acceleration comes into play when data transfer rates are not sufficient to maintain reading/ writing in “streaming mode.” If a host is not sending data fast enough or is not acknowledging the receipt of data soon enough, the drive will slow down through the LTO drive native speed matching capability; but if the data rates fall below a certain threshold, the drive will eventually stop moving tape. When the data stream resumes, the tape drive will move the media backwards a short distance, come back up to speed, and then resume writing. This process is known as “back hitching.” Faster acceleration means back hitch cycles take less time to execute. In environments where back hitching occurs regularly, a FH drive will have a clear advantage over a HH drive.
- **Greater immunity to shock and vibration:** The base plate in the FH LTO-9 is made of aluminum compared to a composite base plate used in the HH drive. The metal base plate provides significantly more immunity to shock and vibration as illustrated by the enhanced specifications of the FH drive versus the HH drive.
- **Higher cartridge insertion force tolerance:** FH LTO-9 drives can handle much greater insertion force, and a greater range of force, compared to HH drives. The mechanism is simply more robust as there is room for larger components. The vast majority of LTO drives and media are installed in automated tape libraries, which are designed to handle media within the insertion force specifications. That said, clearly a more robust mechanism is an

advantage. This is particularly true when the library will be mounting/dismounting tapes at a high rate in archive use cases where the FH drive is rated to handle 300,000 load/unload cycles, compared to 80,000 cycles for HH drives.

- **Higher performance:** As with LTO-8 previously, LTO-9 FH drives have higher performance (throughput) than LTO-9 HH drives. Just as important to note is that the performance gap is widening. HH drive performance has remained the same for three generations, while FH performance has steadily increased. This is due to a combination of factors, including larger motors and heavier more stable mechanical assemblies. While HH drives may have increased performance in future generations, it is unlikely they will ever again be able to match FH drive performance.



**Features and timing:** Due to the limited amount of space for mechanics and electronics, and the increased technical challenges that arise with HH drives, there are differences in features and release timing.

- With LTO-9, FH drives are dual ported, and HH drives have only a single data port. Dual-ported drives provide a level of redundancy and failover protection that is important in environments of all sizes. The ability to keep tape drives operating and available despite network and server disruptions is arguably more important in smaller environments which have fewer tape libraries, tape drives, and servers driving data to them. Single-ported drives cost less to acquire but are not suitable for applications that require a high level of availability.

- As mentioned previously, the new oRAO feature is only available in FH drives.
- FH LTO drives are always released to market before HH drives, with the delay usually measured in months. This is partly due to prioritization, as the same teams work on both drives, but it is also due to the additional technical challenges presented by HH drives. As with any miniaturization effort, squeezing all the important functionality of a FH LTO drive into half the space while retaining the required reliability takes a lot of work, which takes time.

Although both the FH and HH versions of the tape drive have many common characteristics, there are several differences that clearly make the FH drive the better choice for high-duty cycle environments, use cases where the drives will be accessing files that are stored in multiple locations on the same cartridge, and also where the drives will be required to load/unload many cartridges during normal use. This factor is particularly true for archive use cases as well as where the LTO LTFS is being used.



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